National Aeronautics and Space Administration

RADIOISOTOPE POWER SYSTEMS

In-Situ Science Instruments in a Radioisotope Power System Environment

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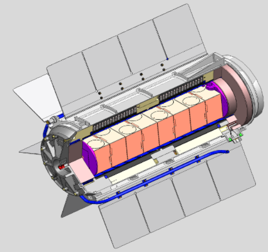
POWER TO EXPLORE

Introduction

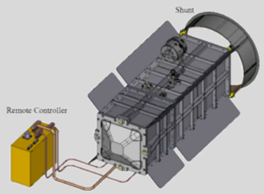
- There is much interest in in-situ missions to the atmospheres, surfaces, and interiors of Europa, Titan, and other destinations.
- These missions would have significant challenges to overcome, including:
  - Tight constraints on mass and volume
  - Power generation where solar power is infeasible, potentially for long duration missions
  - Development of instrument packages necessary to carry out ambitious science investigations, such as the search for signs of life.

Radioisotope Power Systems

- Radioisotope Power Systems (RPS) are enabling for many deep space mission concepts, particularly for outer planet destinations
- RPS use the decay of a radioisotope (Pu-238) as a heat source, and convert the heat to electrical power via various methods.
  - Radioisotope Thermoelectric Generators (RTGs) use Thermoelectrics (TE), which create a voltage via the Seebeck effect.
  - Stirling Radioisotope Generators (SRGs) would use Stirling engines, which use the heat to drive pistons and then convert the motion into electricity.
- Current RPS use general-purpose heat source (GPHS) modules as heat sources
  - For the purpose of this assessment, each GPHS module is assumed to produce 250 W_{th} at beginning of life (BOL)

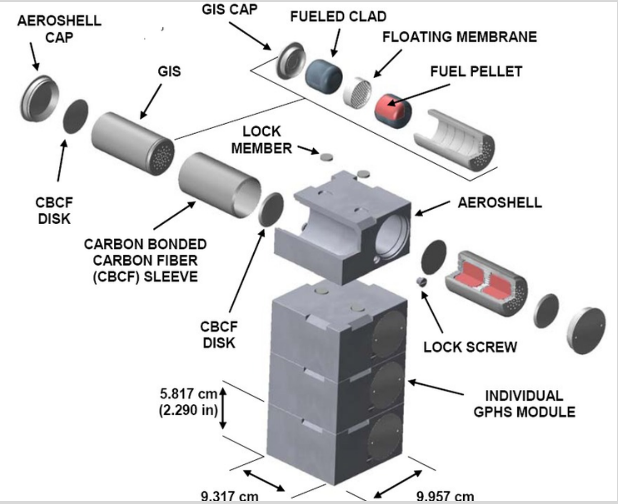


Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)



Advanced Stirling Radioisotope Generator (ASRG) Concept

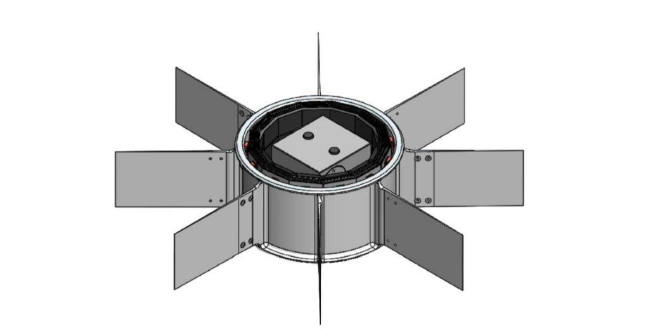
GPHS Exploded View



Next-Generation RTG

- The Next-Generation RTG is a notional modular RTG that could be assembled as a 2 to 16-GPHS system. The option to fly smaller units could be enabling for many in-situ missions.
  - Some design options would only be operable in a vacuum environment – operation in atmospheres would then require a pressure vessel or modified casing.
  - Currently in the initial planning phase; the RPS Program's goal is to develop and qualify the system by 2028

Notional RPS	MMRTG	eMMRTG	2-GPHS Next-Gen RTG	4-GPHS Next-Gen RTG	Unit
BOM Power (4 K, BOL + 3 years)	106	134	52	121	W_e
EOM Power (4 K, BOL + 17 years)	61	94	40	93	W_e
BOM Power (270 K, BOL + 3 years)	105	131			W_e
EOM Power (270 K, BOL + 17 years)	54	93			W_e
Degradation Rate	4.0%	2.5%	1.9%	1.9%	
Diameter	32	32	25	25	cm
Diameter with Fins	65	65	41	51	cm
Length	69	69	22	34	cm
GPHS Heat Load (BOL)	2,000	2,000	500	1,000	W_{th}
GPHS Heat Load (EOM)	1,784	1,784	446	892	W_{th}
BOL Waste Heat	1,880	1,856	445	872	W_{th}
BOL Specific Power	2.8	3.3	5.1	7.1	$W_{e/}$ kg
System Mass	43.6	43.6	10.8	17.9	Kg



2-GPHS Next-Generation RTG concept without closeouts. This graphic is illustrative of a Next-Generation RTG design and does not represent actual hardware or a complete design.

RPS Induced Environments

- RPS could induce environments that impact science instruments and measurements, particularly given close proximity in an in-situ mission.
  - These potential impacts to science instruments must be understood (and mitigated where necessary) to ensure mission success.

Power System Induced Environments	Minimum Level of Impact	Maximum Level of Impact	Environment Impacts on Orbiter Instruments	Mitigation Strategies
Gamma Radiation	< 1 krad over 10 years at 1 meter for 2-GPHS RPS	~25 krad over 10 years at 0.5 meter for 16-GPHS RPS	Damage to sensitive components (memory, ADCs, operational amplifiers). Increase in noise in most detectors.	Shielding, separation, use of less sensitive components
Neutron Radiation	~4E10 n/cm^2 over 10 years at 1 meter for 2-GPHS RPS	~1E12 n/cm^2 over 10 years at 1 meter for 16-GPHS RPS	Single event failures. Detector noise from displacement damage.	Shielding, separation, error correction codes, spike detection and removal, thermal annealing, use of less sensitive components
Thermal	0.5 kW$_t$ for 2-GPHS RPS	4.0 kW$_t$ for 16-GPHS RPS	Need to isolate RPS from radiators, thermal imagers.	Separation, pointing instruments away from RPS, heat shades
Vibration	0 for TE	TBD for potential dynamic RPS	Need to damp vibration for sensitive imagers.	Separation, damping
EMI	Low	TBD for potential higher-power RPS	Detector and magnetometer noise	Separation
Magnetic	< 0.1 nT	< 70 nT at 1 meter	Magnetometer noise.	Separation

Radiation

- RPS are significant sources of radiation. Alpha particles are easily shielded, but RPS also produce gamma rays and neutrons.
- Induced radiation is a function of the number of GPHS modules, and distance between the RPS and the payload.
- At 1 meter separation, the contribution to Total Induced Dose (TID) from RPS would be lower than the environmental dose rate at Mars by an order of magnitude.
  - Impacts limited to instrument noise or to long-term damage to instruments with optical detectors or high-voltage electronics.
- At 0.5 meter separation, for a 16-GPHS RPS, the contribution to TID would be on the order of 2.5 krad/year.
  - Over 10 years, the TID would be ~25 krad/year, which would be on the order of magnitude to the contribution from environmental sources. The total dose would then be 50 krad; using a Radiation Design Factor (RDF) of 2, the payload would need to be designed to be robust up to at least 100 krad.
  - This could be challenging for parts such as operational amplifiers, analog to digital converters, and memory, and can rule out the use of many Commercial-Off-The-Shelf (COTS) parts.
- Atmospheric attenuation of gamma and neutron radiation is negligible on the scale of meters.
- Mitigation strategies include separation and spot shielding (e.g. radiation vaults). Instruments can be qualified to higher doses using more robust designs, radiation characterization, and lot acceptance tests to verify the parts.

Thermal

RPS BOM Thermal Output (Total Heat)

2-GPHS RPS	4-GPHS RPS	8-GPHS RPS	16-GPHS RPS
0.5 kW_{th}	1.0 kW_{th}	2.0 kW_{th}	4.0 kW_{th}

- Shielding the payload from radiated thermal energy is relatively straightforward for spacecraft using booms and radiator shields, but rejecting heat could be more difficult for in-situ missions, especially those in an atmosphere or those that use RPS for subsurface exploration.
  - Potential perturbations from waste heat include warm air plumes, evaporation of rain or lake spray on Titan, or effects on local winds.
  - Meteorological packages and temperature sensors would need to avoid having their measurements possibly contaminated by environmental heating from the RPS.
    - A mast of 1-meter length or more may be necessary.
  - Boats or submarines in a liquid hydrocarbon environment may generate effervescence or fog.
    - For example, Titan lake landers could use insulation on the lower surfaces to try to limit heat flux into the hydrocarbon lake to 10-20 W/m2.
    - Submarines may need to deploy instrumentation away from the vehicle to avoid temperature perturbations and bubbling.

Vibration

- Potential dynamic RPS would use engines with moving parts to produce power. Though they would use compensators or opposed pairs to balance out most of the vibration, there would still be residual effects.
  - The previously in-development Advanced Stirling Radioisotope Generator (ASRG) concept ICD gave a frequency of 102.2 Hz for the vibration, and a value of 35 N for the maximum dynamic force while subsequent testing demonstrated levels of 22 N
- Seismometers could be very sensitive to vibration if they are looking at the same vibration spectrum, but could potentially be mechanically isolated or put in a separate package that is placed on the surface.
- Otherwise, vibration would generally be easier to mitigate for surface and sub-surface in-situ elements than for orbiters, as they could damp vibration through contact with the environment.

EMI and Magnetic Fields

- No EMI issues have been identified for RPS that lie beyond normal environmental specifications.
  - High-power dynamic RPS might generate more EMI. Further design maturation and analysis would be needed.
- The current trend for payload magnetic requirements is 0.1 nT at the magnetometer.
  - Design requirement for notional Next-Generation RTG is < 70 nT at 1 meter, but achieved value could be lower. Further design maturation and analysis is needed.
- Separation is an effective mitigation strategy, as EMI varies with distance as $1/r^2$ and magnetic fields vary with distance as $1/r^2$ on small scales
  - Separation can be more difficult to achieve for in-situ missions.

In-situ Instruments

- In addition to considering power sources, we must consider what instrument technology developments are necessary to proceed with future in-situ missions.
- A study was carried out at JPL to identify potential in-situ instruments, coming up with 45 instrument types. The approach was as follows:
  1. Characterize the missions and destinations of interest for in-situ exploration
  2. Based on these destinations, list science goals
  3. Based on the science goals, develop desired measurements and then identify the necessary instruments.

Sample of matrix of identified instruments

Instrument	Measurement	Flight Model	Notes	Radiation Hard	Power Magnitude	Mass Magnitude	Surface	Aerial	Gaseous (Probe)	Ice	Water Ocean	Hydrocarbon Ocean
Accelerometer	Wind speed, entry dynamics, ocean currents, ice motion	Yes	Mars probes and atmospheric probes.	Yes	0.1	0.1		X	X	X	X	X
Alpha Particle Spectrometer	Ice atomic composition	Yes	APXS (Mars, Rosetta)	Possible	0.1	0.1	X			X		
Conductivity	Ocean salinity, soil conductivity	No	Trivial engineering, MECHA instrument flown	Yes	0.01	0.1	X			X	X	X
Hardness Detector	Ice Composition	Yes	Flew on Huygens probe. Needs some additional work for implementation.	Yes	1	1				X		

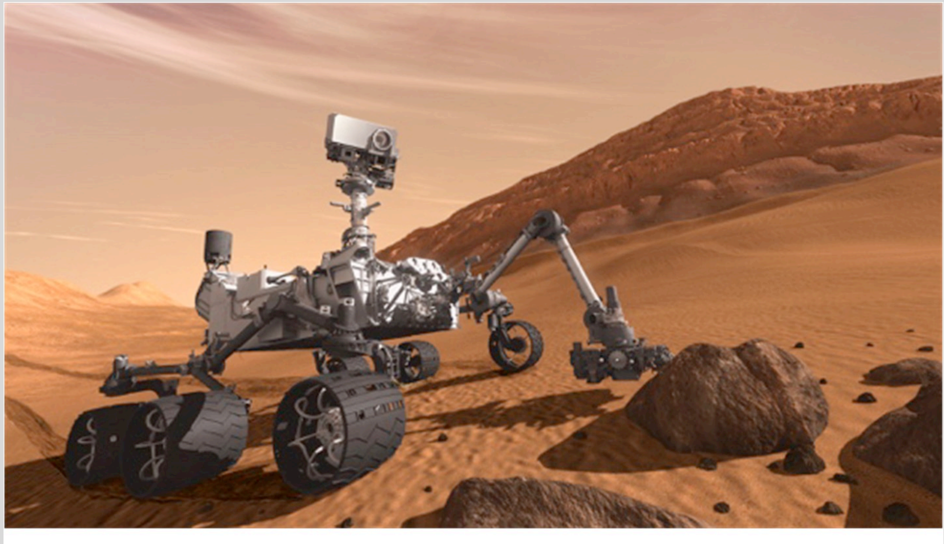
- A survey was done of 20 previous in-situ missions and mission concepts to catalog the instrument types. This effort confirmed interest in the identified instrument types, while suggesting a gap in the capability to answer high-priority questions in biology, organic chemistry, and biochemistry.

Developments for In-situ Science

- The instrumentation required to support in-situ science goals are largely distinct from the catalog of flight instruments that have been used in past orbital missions.
- The shifts in the design of in-situ instruments arise from four factors:
  - Changes in types of sampling—Instruments have to be adapted from making far-field measurements to principally acquiring near-field measurements, including working in aqueous environments, requiring active illumination, and operating in high pressure environments.
  - Changes in envelope for the instruments—Instruments on melt probes, submarine platforms, and atmospheric probes require significant modification to comply with tight packing requirements and form factor restrictions.
  - More focus on biology, organic chemistry, and biochemistry—Many techniques for biological, micro-mineralogic, age dating, and oceanographic measurements have not yet been adapted for flight in both miniaturization and technology readiness for flight. Very high sensitivity measurements and measurements of micro samples and environments are not yet achievable with available instrumentation for remote probes.
  - Sample handling—Probes operating in environments that require pressure vessels, measurements working with very small samples, and experiments utilizing wet chemical techniques require new developments for sample handling mechanisms.

RPS and Instrument Accommodation

- Different in-situ mission types deal with different environments and packaging issues. Several of the most common mission types are discussed here.
- For any environment with an atmosphere (Mars, Titan, etc.), vacuum-only RPS, potentially including the notional Next-Generation RTG, would need a pressure vessel or modified casing.
- Surface – e.g. landers, rovers, boats, hoppers, etc.
  - Landers and rovers typically have designs where RPS can be mounted externally and radiate using fins.
  - Rovers are similar to landers. Mobility benefits from higher available power. Mounting would need to handle stresses from mobility.
  - Instrument considerations for surface elements include methods for taking samples and a way to form a strong surface contact for seismology.



Curiosity Rover

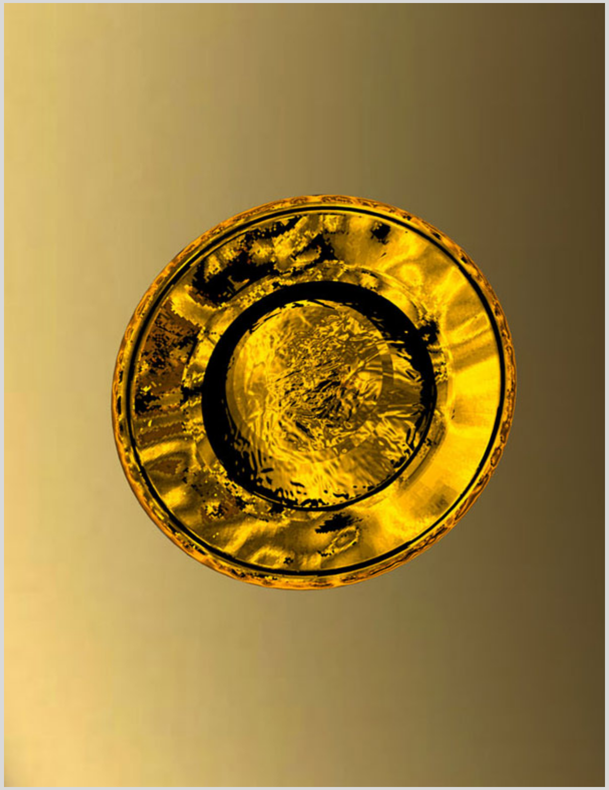
RPS and Instruments – Aerial Missions

- Aerial – e.g. helicopters, fixed-wing aircraft, and balloons
  - Mass is a key constraint.
  - Fixed-wing aircraft would have form factor constraints due to aerodynamics.
  - Compared to solar powered missions, RPS would free aerial elements from issues with pointing towards sun and low irradiance within clouds.
  - Hot-air style balloons could benefit from waste heat from RPS.
  - Accommodating instruments would not pose any particular challenges for aerial missions except in the Venus environment, where the high pressure and corrosive atmosphere might require a pressure vessel to protect the instruments.

Titan Saturn System Mission
Montgolfiere Concept

RPS and Instruments – Atmospheric Entry

- Atmospheric Entry – probes such as the Cassini-Huygens probe
  - Atmospheric probes can be categorized as floaters and sinkers. Sinkers (e.g. Galileo and Huygen's probe) have lifetimes of 1-2 hours and are typically battery powered. Floaters could have lifetimes of weeks to months, and would typically circumnavigate the object. These longer-duration missions could greatly benefit from RPS, due to issues with pointing at the Sun or with atmosphere blocking sunlight.
  - Floaters would typically be balloons or blimps, so see the Aerial section for constraints regarding mass, form factor, atmosphere, and instruments.



Cassini-Huygens Probe

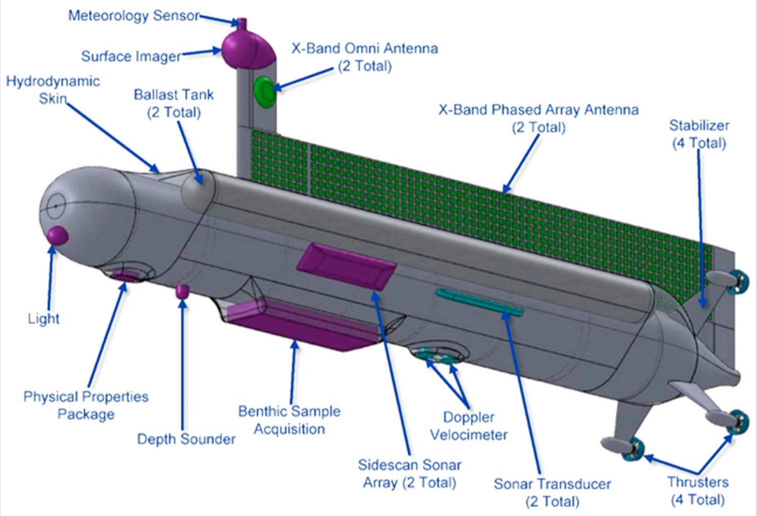
RPS and Instruments – Ice Missions

- Ice – subsurface ice explorers such as melt probes or drills
  - Ice explorers such as melt probes could make great use of RPS for both power and heat – on the order of 4 kW_t.
  - Mass is a significant constraint because the probe would need to be landed.
  - Form factor is a significant constraint because transit time through the ice is inversely related to probe diameter and length; a practical limit to the dimensions is a 30 cm diameter and a 2 m length.
  - The subsurface ice environment can reach very high pressures of 100+ bar. The RPS and instruments would need to be contained within a pressure vessel.
  - Instruments would need to be miniaturized, would need inlets through the pressure vessel to take measurements, and would need to be separated from the RPS as much as possible to limit TID.

VALKYRIE Cryobot Prototype

RPS and Instruments – Ocean Missions

- Ocean – e.g. submarines, bathyspheres, and buoyant rovers
  - An ocean explorer in an ocean under an ice shell would need to be delivered there through the ice. It would thus have the same issues as in the Ice section regarding volume, aspect ratio, pressure vessel, and thermal considerations.
  - Once delivered, an ocean explorer would need to operate in an aqueous environment. Submarines would have to consider solutions for mobility, telecom, tracking location, telemetry, illumination, and buoyancy control. Mobility and telecom especially benefit from higher available power.
  - Rejection of waste heat can be an issue without strong interaction with local environment due to boiling cryogenic fluids. For instance, a submarine in a surface lake on Titan would be operating in a hydrocarbon fluid at 90 K. This could cause problems with heat from the submarine and the RPS, due to generating gas, blinding instruments with bubbles, and/or changing the buoyancy.



Titan Lake Submarine Concept (NASA / JHU-APL)

Conclusions

- RPS can be enabling or enhancing for many in-situ mission concepts, allowing for new measurements and investigations
- Instrumentation may need development for many of these missions, especially for aqueous environments for melt probes and submarines.
  - Many of the goals for in-situ missions are organic or biochemical in nature; the amount of instrumentation that can be accommodated in an in-situ mission is limited and may not be adequate at current instrument sizes.
  - Instrument development and future RPS development are ongoing, giving the opportunity to design each to accommodate the other.
- Potential RPS impacts on in-situ elements and payloads are most significant in the radiation and thermal categories.
  - Volume constraints could necessitate close proximities of instruments to RPS, producing TID levels that would need to be mitigated with spot shielding or more robust instrument design.
  - Waste heat from RPS could make changes to the local environment, particularly for missions in the thick Titan environment, or for ocean explorers. Mitigations include insulation, separation, or reducing the heat load by using smaller RPS or more efficient RPS.

Questions?